Top quark in theory

Hadron Collider Physics workshop
Galena, IL, May 2008

Eric Laenen

NIKHEF

University of Amsterdam

Top: Star of the Hadron Colliders

- Most expensive, most glamorous
- Interacts with everybody, especially with those who matter
- Promises major, tell-all revelations real soon now
- Will be center of attention while..
- ... until a new star comes along..

Top: Star of the Hadron Colliders

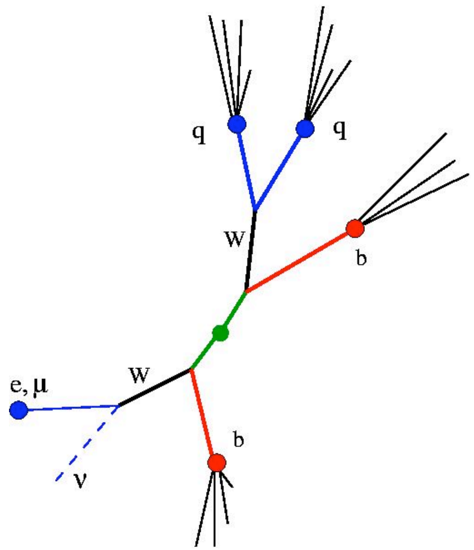
- Most expensive, most glamorous
- Interacts with everybody, especially with those who matter
- Promises major, tell-all revelations real soon now
- Will be center of attention while..
- ... until a new star comes along..

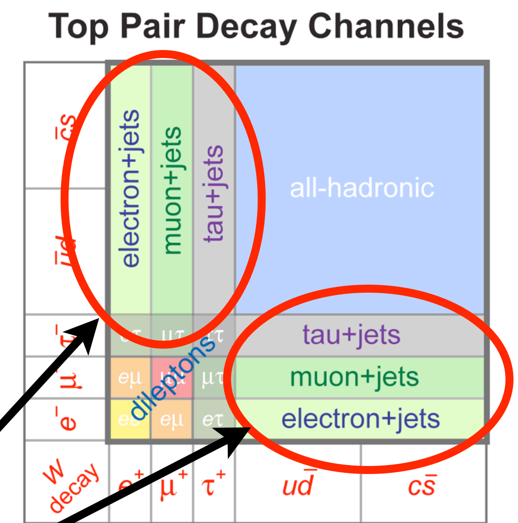
Top is special

- It has lots of quantum numbers, couples to pretty much everything..
- ..through chiral, vector, scalar structures (SM)
- Large mass
  - strong coupling to EWSB mechanism
  - good for pQCD, no hadronization
  - spin information preserved due to rapid decay
- Top is trouble maker for SM (quadratic divergences...), enabler for MSSM, Little Higgs...
- *Top Mission*: check its behavior, very carefully.
- Tevatron made the first precious few, now many more. LHC a top factory

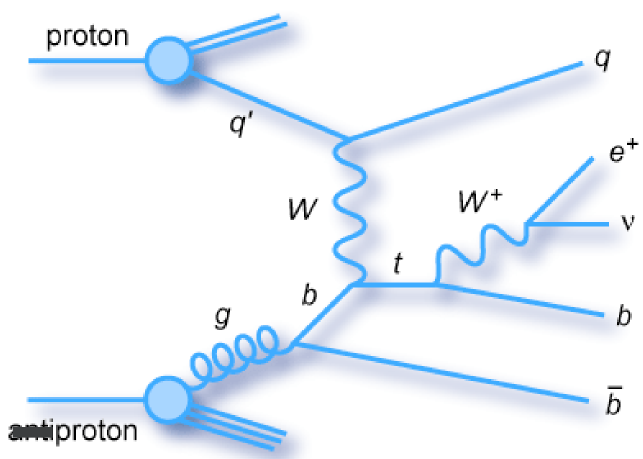
Recent excellent reviews by Han, and Bernreuther

LHC: T-factory





- Pairs: 8 MEvents/year (x 10)
- after 10 fb^{-1}: 70K lepton + jet events



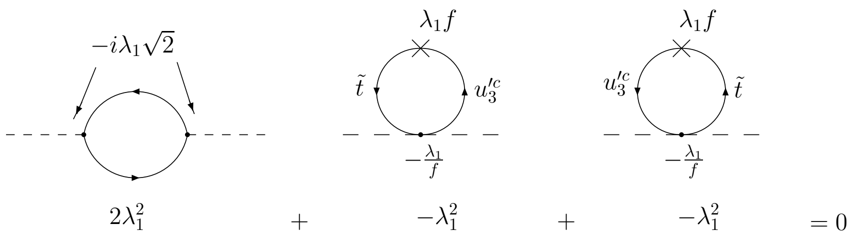
- Single: 2 MEvents/year (x 10)
- after 10 fb^{-1}: 5K events

Top will immediately be used for calibration

Top and Little Higgs

Little Higgs models: Higgs is a pseudo-Goldstone boson, therefore light

- Symmetries forbid one-loop Higgs mass term: solves little hierarchy problem
- ..which was caused, anyway, mostly by top loop corrections
- Little Higgs models cancel (top) quadratic divergences with similar particles of same spin (vectorlike top T e.g.)



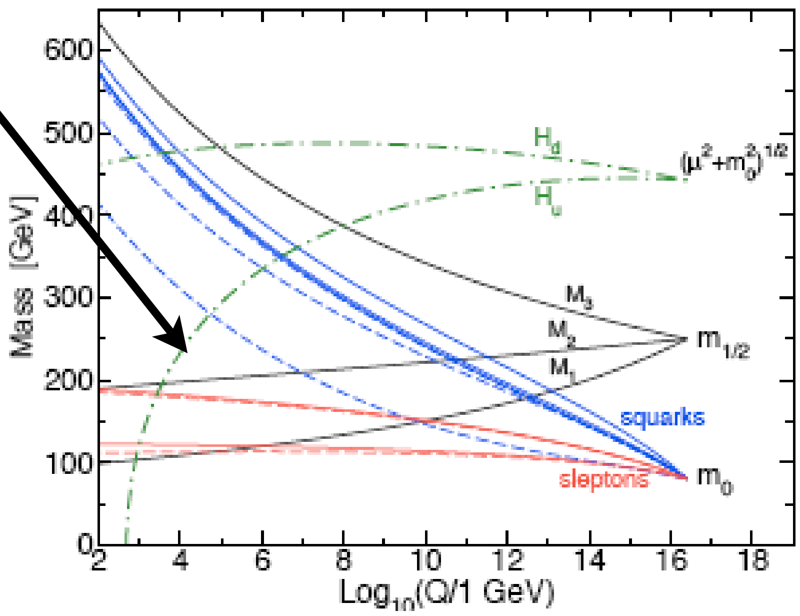
Han, Logan, Wang

Good number of models (gauge groups, T-parity), can be unraveled

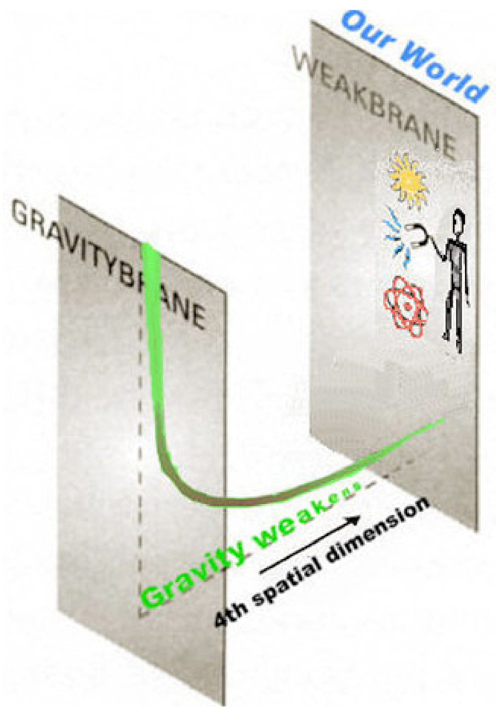
- measuring couplings in the top, T sector, and m_T (cross section 0.01-100 fb)
- test vector character of T

Top and SUSY

- Keeps MSSM alive via (top, stop) corrections on lightest Higgs mass
- Radiative EW symmetry breaking
- Many LHC SUSY signals involve top, or top mimics them
- Heavy Higgses may decay to top, can determine their CP properties



Top and extra dimensions

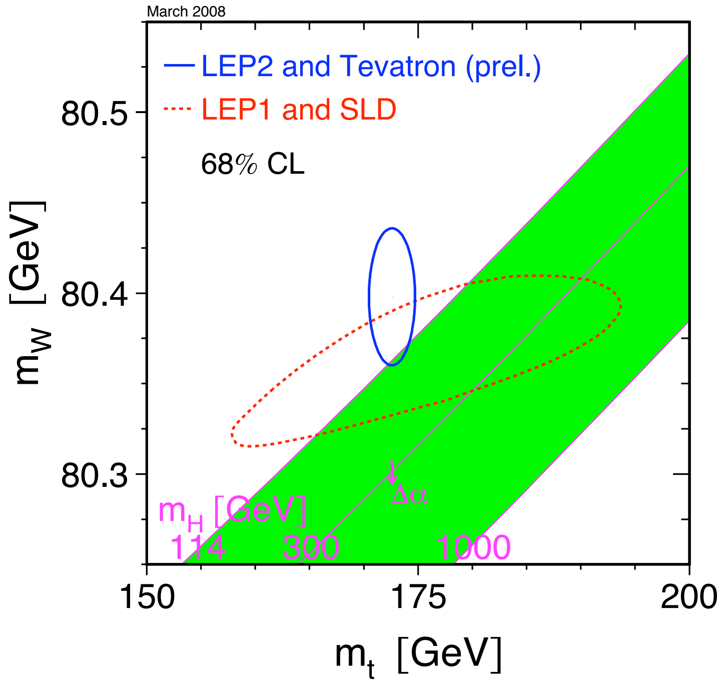


New particles, Kaluza Klein modes

- Gluon KK modes show up as resonances in reaction gg →tt
- Angular distributions of top decay leptons can distinguish scenarios

Top mass

$\Gamma_t \cong 1.28$ GeV

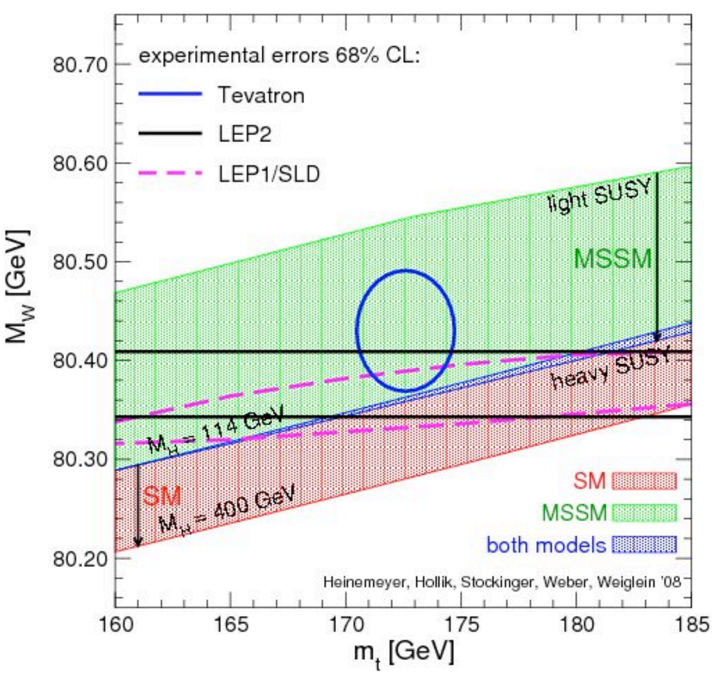


now: 172.6 ± 1.4 GeV (Tevatron)

<1% !!

- Measure via reconstruction of final state, or via cross section
- Relate m_W, m_t, m_H to constrain SM, MSSM

Heinemeyer, Weiglein



Top mass

- LHC: accuracy of 1 GeV possible→ 6 MeV accuracy of m_W at fixed m_H
- Experiments reconstruct approximately the pole mass from decay products
- Better mass definition perhaps through $t\to b(\to J/\psi) + l\nu$ at LHC Karchilava, otherwise wait for (I)LC Fleming, Hoang, Mantry, Stewart; Beneke, Signer; Hoang
- Some measurements use theoretical cross section. Use distribution in M_{tt} ? Frederix, Maltoni

A bit of threshold resummation

All order sum of large logs

1. $\sum_n \alpha_s^n \ln^{2n}(s - 4m^2) \quad [\sigma(s)]$
2. $\sum_n \alpha_s^n \ln^{2n}(s - 4(m^2 + p_T^2)) \quad [d\sigma(s)/dp_T]$
3. $\sum_n \alpha_s^n \ln^{2n}(s - 4(m^2 + p_T^2)\cosh y) \quad [d^2\sigma(s)/dp_T dy]$

- "Threshold" depends on observable.
  - *But note:* for total cross section, one *could* use all three.
- For ease, first take moments of (s-4m^2) etc $\quad \sum_n \alpha_s^n \ln^{2n} N$
- Then resum. Then, undo moments

A bit of threshold resummation

✓ Logs L from soft/collinear gluons, can be summed to all orders

$$
\begin{aligned}
\hat{O} &= 1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \ldots \\
&= \exp\left(\underbrace{\underbrace{Lg_1(\alpha_s L)}_{LL} + g_2(\alpha_s L)}_{NLL} + \alpha_s g_3(\alpha_s L) + \ldots \right) \underbrace{C(\alpha_s)}_{\text{constants}} \\
&\quad + \text{ suppressed terms}
\end{aligned}
$$

✓ Many ways to derive exponential form

✓ Algebraic proof: "eikonal" perturbation theory is exponent of "web" diagrams

✓ For Higgs/Drell-Yan inclusive cross section:

$$
\hat{\sigma}_i(N) = C(\alpha_s) \times \exp\left[\int_0^1 dz \frac{z^{N-1} - 1}{1 - z} \left\{ 2 \int_{\mu_F^2}^{(1-z)^2 Q^2} \frac{d\mu^2}{\mu^2} A_i(\alpha_s(\mu^2)) + D_i(\alpha_s(1 - z)Q^2) \right\} \right]
$$

✓ A: Cusp anomalous dimension. D: known to 3rd order

✓ Similar for top, but D is a *matrix in color space*

Sterman; Catani, Trentadue, Gatheral, Frenkel, Taylor, Grazzini, de Florian, Forte, Ridolfi, Vogelsang, Kidonakis, EL, Magnea, Moch, Vogt,Vogt, Eynck, Ravindran, Becher, Neubert, Ji, Idilbi,...

Updated theoretical top cross section

- ✓ NLL resummed, with exact NLO
- ✓ Tevatron top near threshold, LHC not so much
- ✓ Since 2003 better PDF's, new results in resummation
- ✓ CTEQ6.5, MRST2006-NNLO
- ✓ Time to update the inclusive top cross section, and its errors

Cacciari, Frixione, Mangano, Nason, Ridolfi

- ✓ Vary μ_R, μ_F independently, conservatively
- ✓ No error combinations
- ✓ At LHC: scale uncertainty >> PDF uncertainty
- ✓ Tevatron: 10% LHC: 10 % (NLO-NLL)

Moch, Uwer

- ✓ Vary μ_R, μ_F
- ✓ Linear error combinations
- ✓ Tevatron: 7% LHC: 5% (NNLO-approx)

Nadolsky, Lai, Cao, Huston, Pumplin, Stump, Tung, Yuan

- ✓ Vary $\mu_R = \mu_F$
- ✓ CTEQ6.6
- ✓ Use cross section as gluon probe, standard candle

Moch, Uwer

Approximate NNLO cross section

Resummed cross section
$$\frac{\hat{\sigma}^{N}_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)}{\hat{\sigma}^{(0),N}_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)} = g^{0}_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)\cdot\exp\left(G^{N+1}_{ij,I}(m_t{}^2,\mu_f^2,\mu_r^2)\right)$$

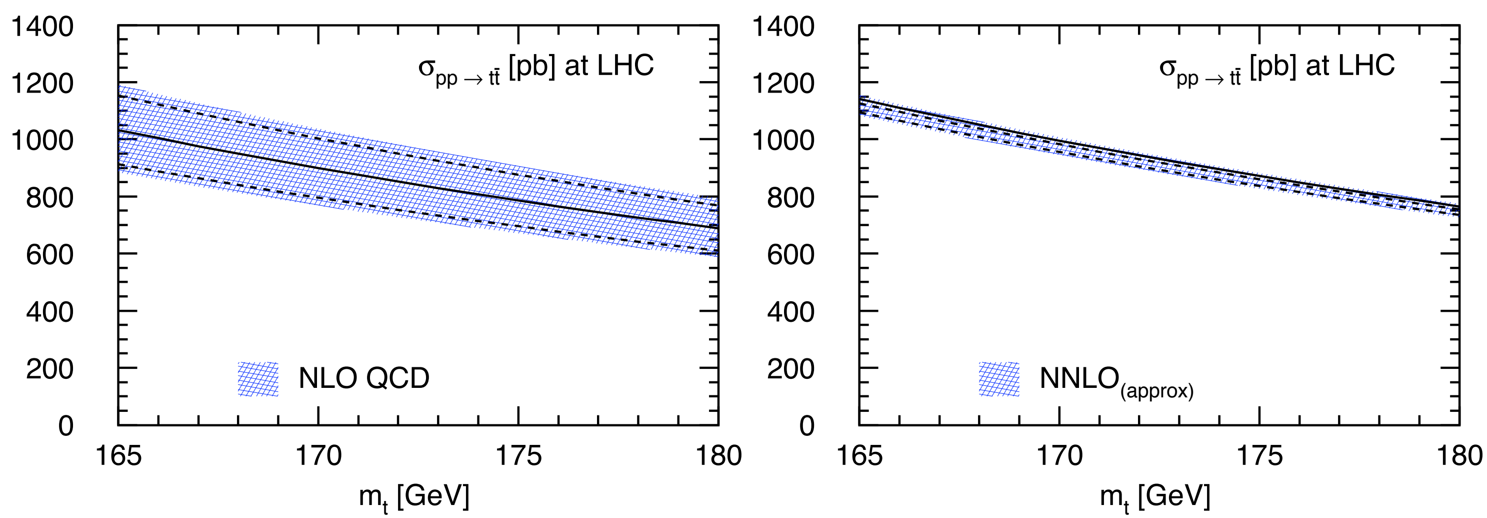
Exponent:
$$G^{N}_{q\bar{q}/gg,I} \;=\; G^{N}_{\mathrm{DY/Higgs}} - \delta_{I,8}G^{N}_{Q\bar{Q}}\,,$$

Aybat, Dixon,Sterman

Remarkable: Known to 3 loops — Known to 2 loops !!

Result:
$$\alpha_s^2\sum_{n=0}^{4} c_n \ln^n\beta \;+\; \text{Coulomb}, \qquad \beta=\sqrt{1-\frac{4m^2}{s}}$$

Other thresholds?



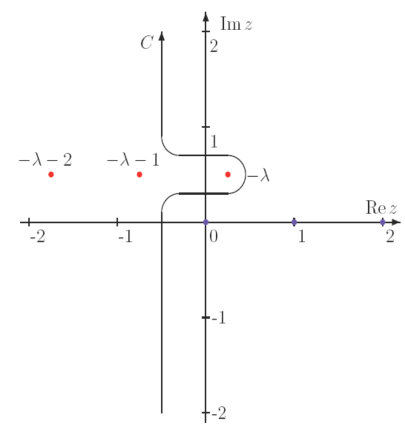
Perhaps too small?

Exact NNLO top cross section?

Czakon, Mitov, Moch

- Full exact NNLO 2 →2 does not yet exsit massless partons
- Part of real corrections (1 virtual + 1 emission) known (Dittmaier, Uwer, Weinzierl)
- Virtual corrections now computed for $m_t^2 << s,t,u$
  - $\log(m_t)$ from Factorization + 2-loop massless results (Mitov, Moch)
  - Direct calculation via Mellin-Barnes (Czakon) methods
- Now also large m_t virtual results

$$\frac{1}{(A+B)^\nu} = \frac{1}{\Gamma(\nu)} \frac{1}{2\pi i} \int_C dz \frac{A^z}{B^{\nu+z}} \Gamma(-z)\Gamma(\nu+z)$$

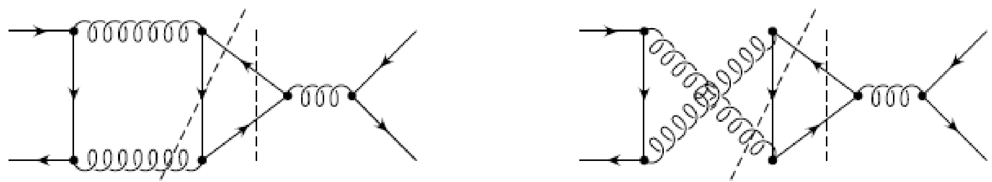


Charge asymmetry

aka forward-backward asymmetry

CDF: 24 ± 13 ± 4 %

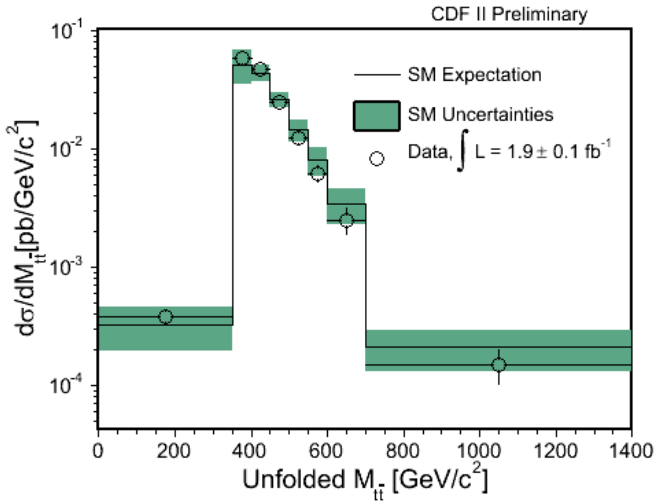
D0: 12 ± 8 ± 1 %



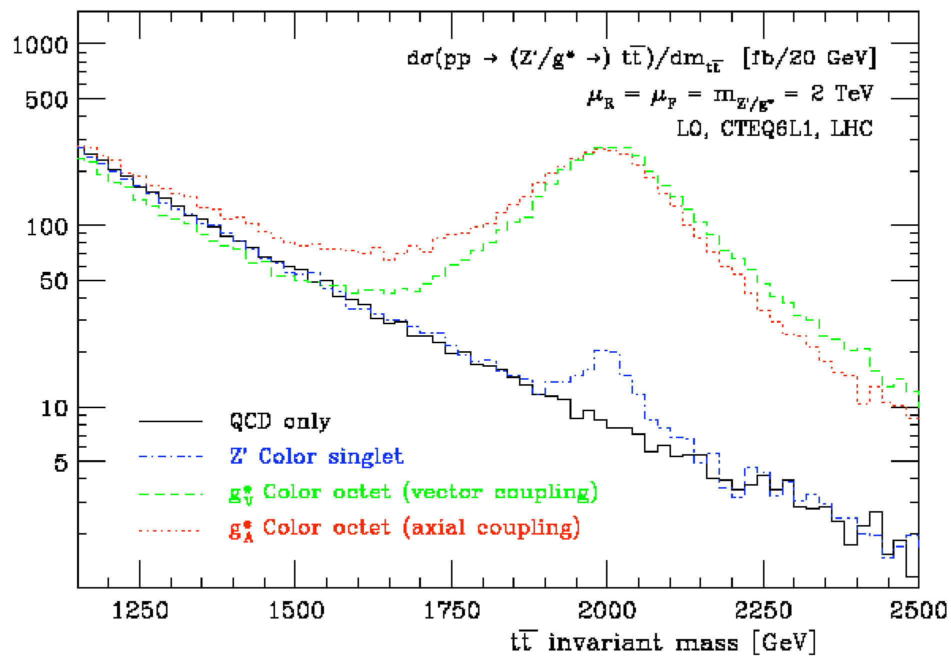
- Rate difference of top vs. anti-top at fixed angle (or rapidity)
- At LO from Electroweak, or BSM mechanisms
- Shows up in QCD first at $O(\alpha_s^3)$ through (a) interference Born-Virtual, or (b) radiative. Nason, Dawson, Ellis; Beenakker, Kuijf, van Neerven, Meng, Schuler, Smith
- Interference of C-odd and C-even amplitudes. Proportional to SU(3) d_{abc} Rodrigo, Kuhn
- NLL threshold resummation [Almeida, Sterman, Vogelsang] for charge asymmetry from that for $$\frac{d\sigma^{t\bar{t}}}{dM_{t\bar{t}}\, d\cos\theta}$$ Kidonakis, EL, Moch, Vogt; Kidonakis, Sterman
- Sizeable enhancement at large M_{tt}, but overall moderate, and more accurate

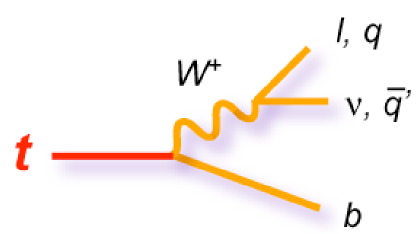
Pair-invariant mass distribution

Frederix, Maltoni



- Sensitive to many SM extensions decaying to top pairs
- Bottom-up approach, don't assume full model
- Use MC@NLO, Madgraph
- Study of (pseudo) scalar, vector, spin-2 resonances. Gives masses, widths, parity, spin. Interference matters.

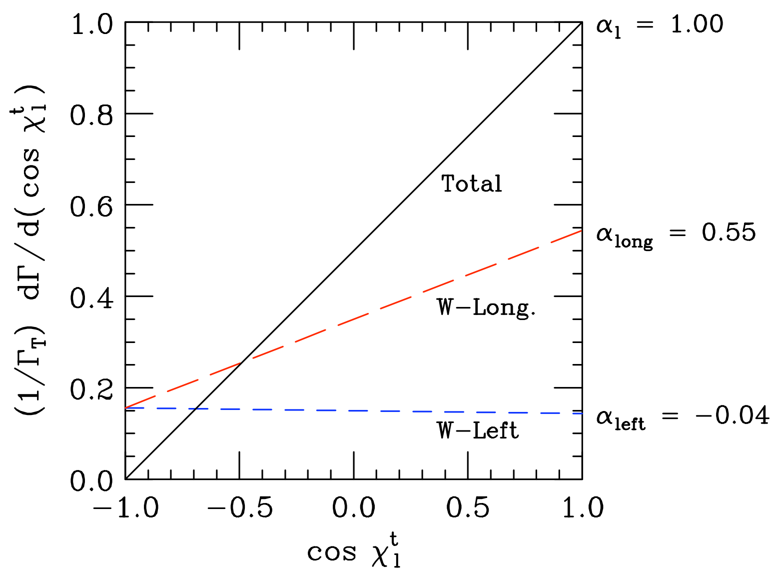




Top decay: spin

$$\frac{d\ln\Gamma_f}{d\cos\chi_f} = \frac{1}{2}(1+\alpha_f\cos\chi_f)$$

- Top self-analizes its spin: 100% correlation ($\alpha_f = 1$) of t-spin with l^+-direction
- QCD corrections to α_f very small
- Worthy of verification (e.g. charged Higgs decay would lower α_f)
- Powerful probe of spin quantum numbers of top, and any process that produced it (single top, resonance,..)



Higher order top production

Much recent progress:

- Associated production at NLO (3+ particles in final state at LO)
- Monte Carlo descriptions, both parton-shower and matrix-element based
- Top spin included

$t\bar{t}$ + Higgs to NLO

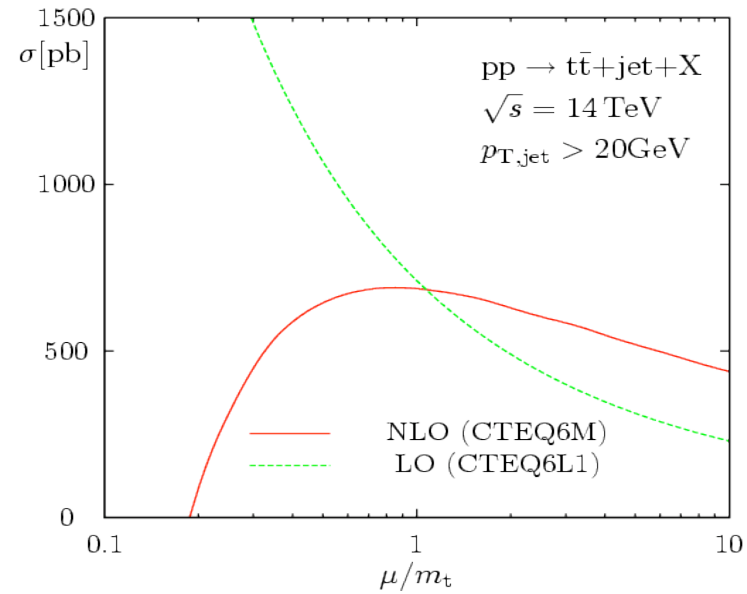
Beenakker, Dittmaier, Krämer, Plumper, Spira, Zerwas;
Dawson, Jackson, Orr, Reina, Wackeroth

- Helps measure top yukawa coupling
- Early studies: excellent for discovering light Higgs ($\rightarrow$ bb)
- Recent studies [ATLAS,CMS]: backgrounds probably too hard for Higgs discovery
- NLO 2 $\rightarrow$3 process with different masses feasible, both for phase space slicing and subtraction methods
- Spin-off: bb $\rightarrow$ Higgs (for MSSM) (Harlander, Kilgore; Maltoni, Sullivan, Willenbrock)

Dittmaier, Uwer, Weinzierl

$t\bar{t}$ + jet to NLO

- Helps unravel top pair production, sensitive to new physics
- Important background to many BSM signals
- Possibly measure top charge asymmetry in pp
- Theoretical testing ground: 2 →3 full QCD at NLO, with mass, and complicated color structure
- Many advanced techniques used (novel reductions, dipole method, Berends-Giele recursion). Two fully independent calculations
- Computer algebra crucial



Differential distributions (almost) ready

$t\bar{t}$ + spin correlations at NLO

Bernreuther, Brandenburg, Fücker, Si, Uwer
Mahlon, Parke

- At LHC, tops in pair production are produced essentially unpolarized
- But they do have clear mutual spin correlation

$$\frac{d\sigma}{d\cos\theta_a \cos\theta_b} = \frac{\sigma}{4}(1 + B_1 \cos\theta_a + B_2 \cos\theta_b - C\cos\theta_a \cos\theta_b)$$

- C depends on quantization axis, highest in helicity basis in zero momentum frame
  - $C_{hel} = 0.326$ $(C_{beam} = -0.07)$

Top and Monte Carlo

Tree-level, high multiplicity matrix elements, matched to parton showers

- Alpgen: tt + ≤ 6 jets (uses ALPHA algorithm, MLM matching, with spin)
- MadEvent: tt + ≤ 3 jets (uses helicity amps, various matchings)
- CompHep: tt + ≤ 1 jets (squared matrix elements, with spin)

Next-leading order (includes virtual corrections), matched to parton showers

- MC@NLO: tt + ≤ 1 jet (spin included)
- POWHEG: tt + ≤ 1 jet

Frixione, Webber

MC@NLO

Expanded parton shower

$$\frac{d\sigma}{dO} = \int_0^1 dx \Big[I_{MC}(O, x_M(x)) \frac{\alpha(R(x) - B\,Q(x))}{x} + I_{MC}(O, 1) \frac{B + \alpha V + \alpha B(Q(x) - 1)}{x} \Big]$$

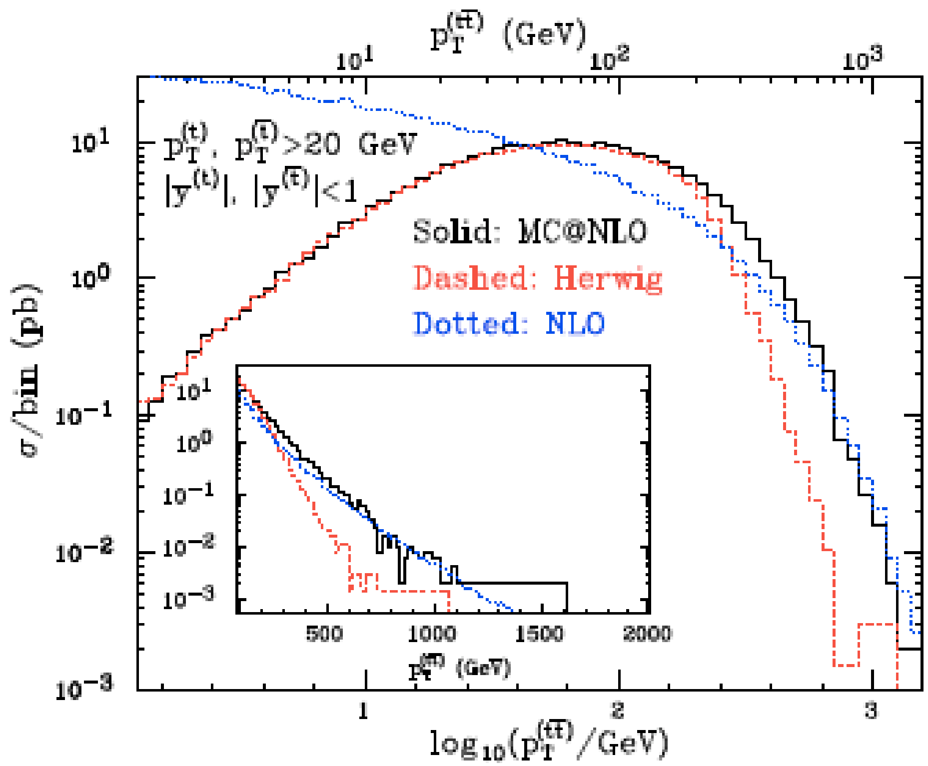
Interface to parton shower

- MC@NLO outputs events
- Events have weight +1 or -1 (< 15%)
- Showers from hard processes of NLO cross section, 2→2 and 2→3
- Inclusive rate is σ(NLO)
- Expand shower, and subtract to avoid double counting

MC@NLO and $t\bar{t}$

Frixione, Nason, Webber

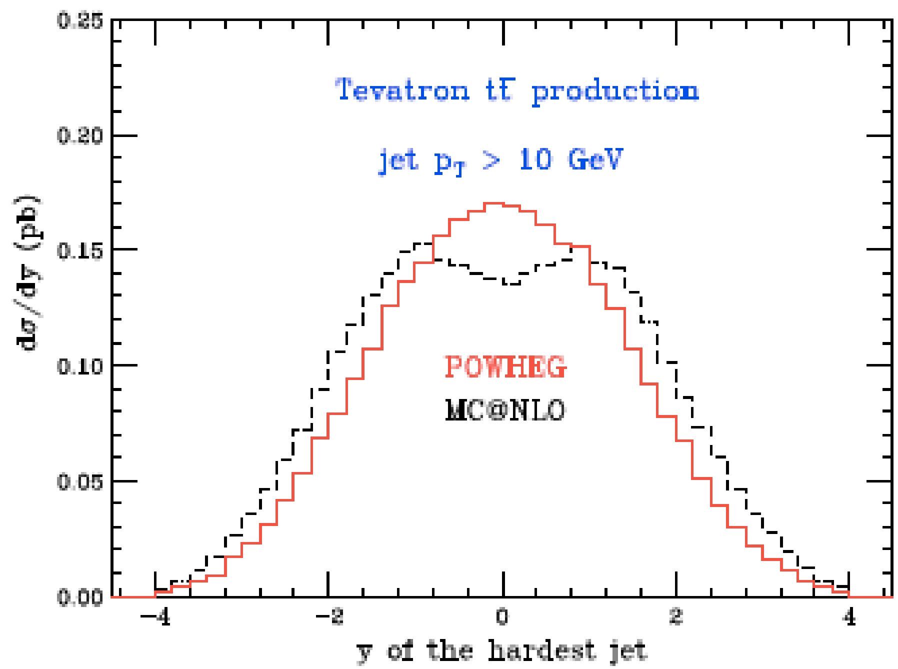
- First process in MC@NLO with final state colored partons, multiple color flows
- Interpolates well between large hard matrix element behavior, and softer physics dominated by parton showers



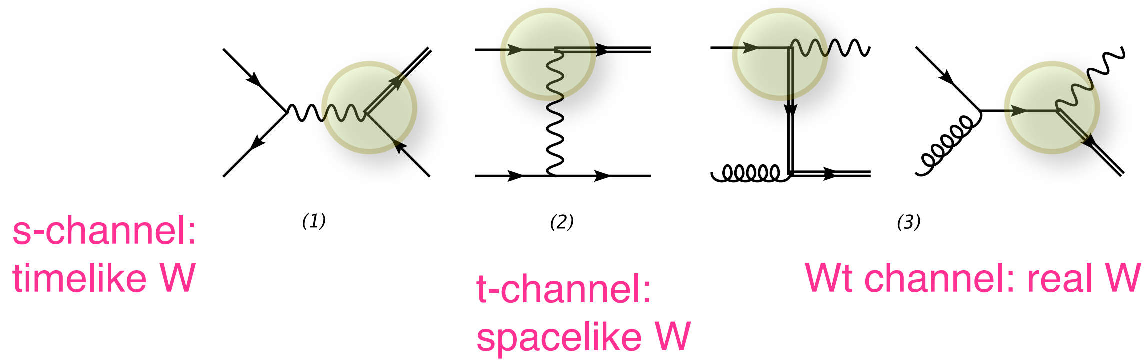
Top MC comparisons

With MC descriptions of top physics very central, it is important to understand differences

- POWHEG (Nason; Oleari, Frixione no negative weights, different showering) vs MC@NLO
- MC@NLO vs. ALPGEN for tt+jet



Single top at NLO



Important process for LHC

- Allows measurement of V_{tb} per channel
- Easier check of chiral structure of Wtb vertex than tt
- Infer the b-density
- Sensitive to FCNC's (t-channel), or W' resonances (s-channel)

Harris,EL,Phaf,Sullivan, Weinzierl; Cao, Schwienhorst, Yuan; Zhu; Campbell, Ellis, Tramontano

σ(NLO)	s-channel [pb]	t-channel [pb]	Wt-channel [pb]
Tevatron	0.90	2.00	0.00
LHC	10.20	245.00	60.00

V_{tb}

- In SM constrained to be 0.9998 by unitarity
- Less is more → extra fermions
- E.g. if extra vector-like quark, or 4th generation, $V_{tb} > 0.8 - 0.9$, depending on assumptions Alwall et al [Louvain]

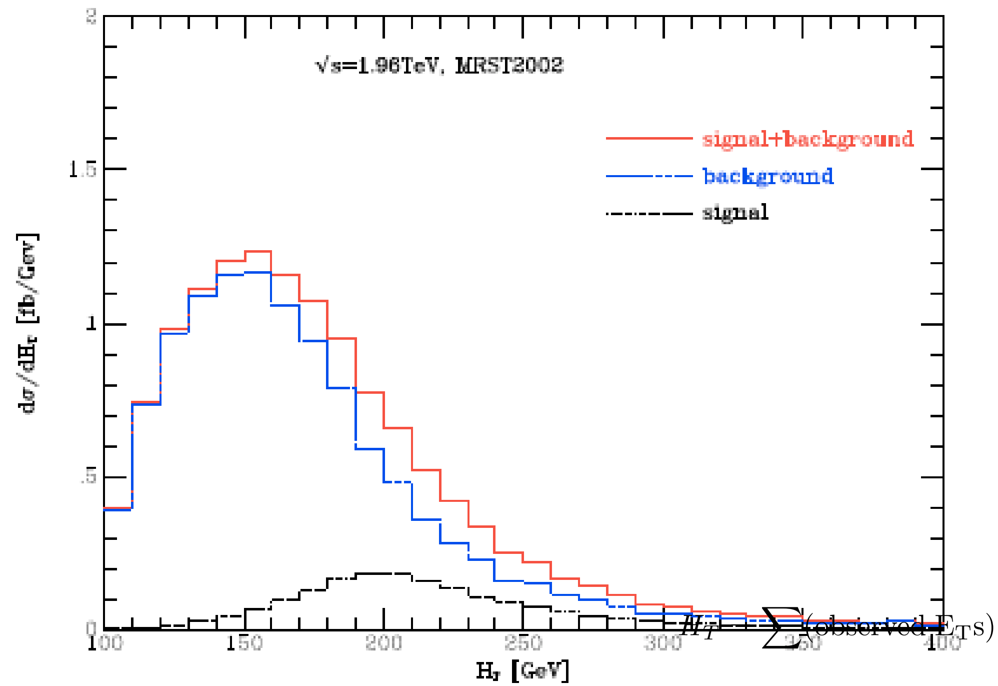
Single top at NLO, cont'd

Differential distributions at NLO

D0: 3.4 σ evidence for single top
CDF: σ = 2.2 ± 0.7 pb, [3.7 σ evidence]

- Calculated with about all phase space slicing and subtraction mechanisms known to Man
- Top spin, in NWA, included using NLO density matrix

Campbell, Ellis, Tramontano [MCFM]



Signal: lepton, E_T-miss, 2j (1b)
Bkgd: W+ 2j, tt, mistags

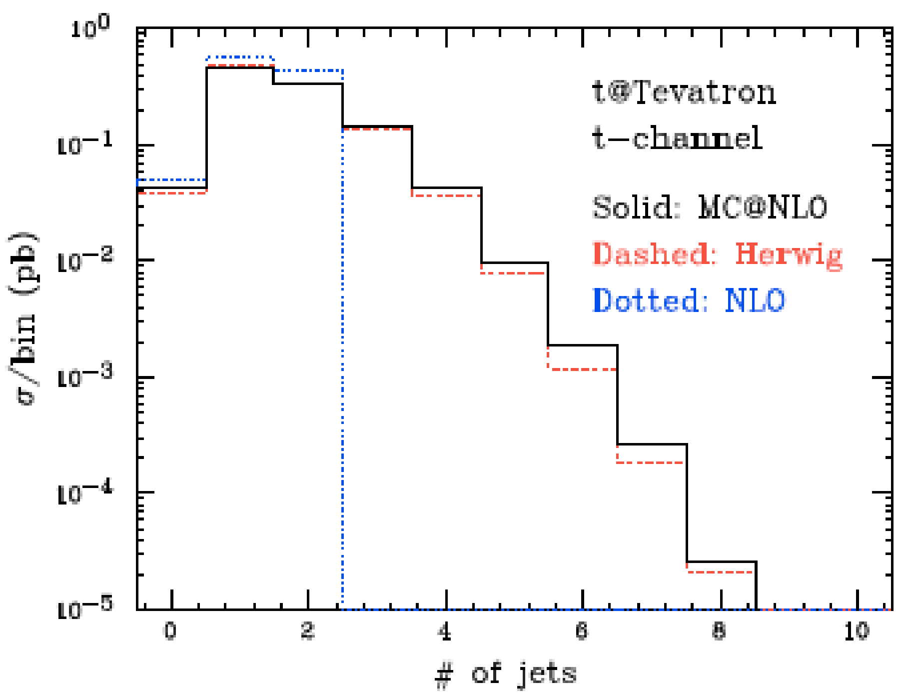
Single top in MC@NLO

Frixione, EL, Motylinski, Webber

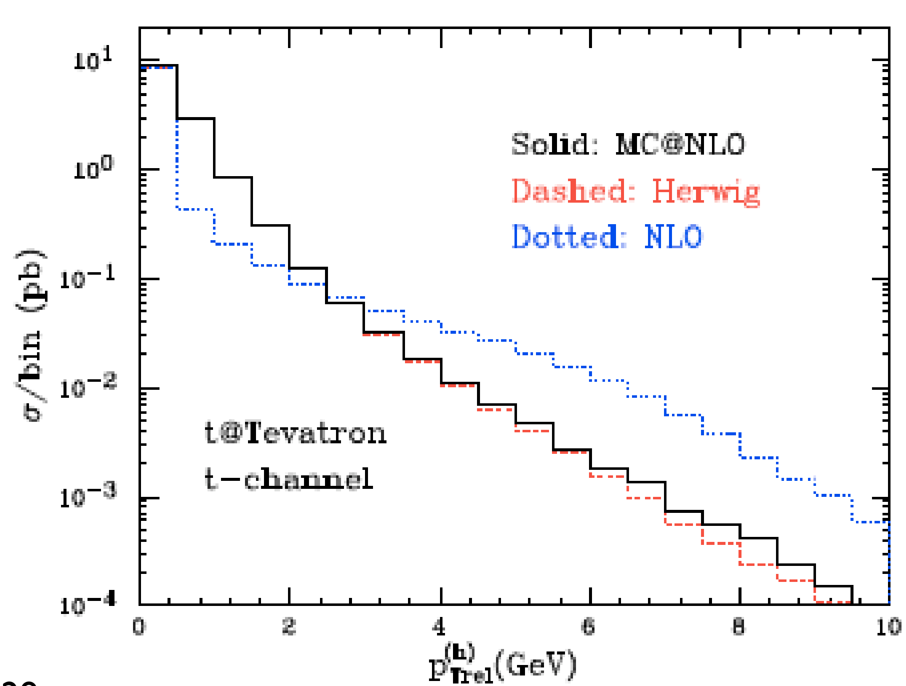
Adds MC@NLO benefits to this process, but also

- required extension of MC@NLO to final state jets
- simplified subtraction method

Number of jets



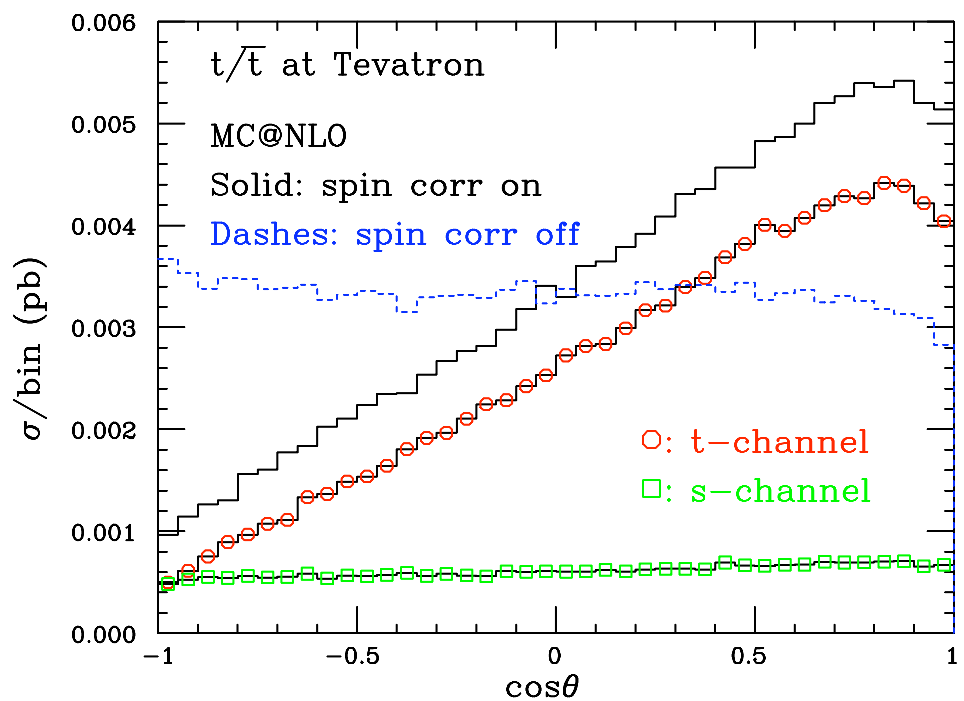
pT relative to jet axis in hardest light jet



Spin correlations for single top in MC@NLO

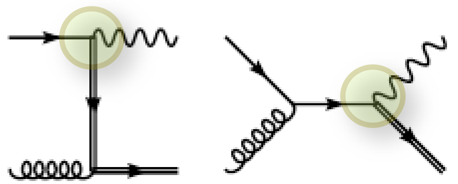
Frixione, EL, Motylinski, Webber

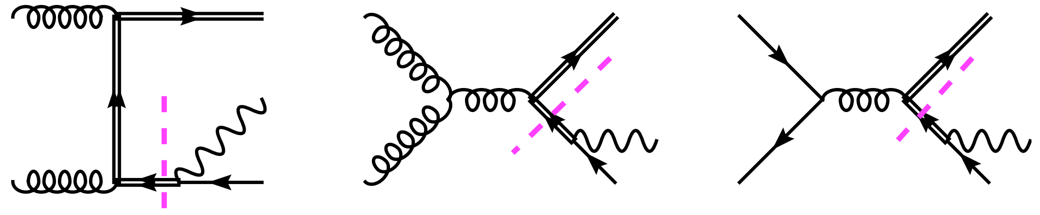
- Top is produced polarized by EW interaction
- Angular dependence discriminates channels: here t-channel quantization axes



Frixione, EL, Motylinski, Webber, White

Single top in Wt mode meets tt..





+ non-resonant diagrams

Serious interference with pair production (10 times bigger)

- Clean solution: compute WWbb (Kauer, Zeppenfeld), don't separate
- Previous: cut on invariant Wb invariant mass (Belyaev, Boos, Dudko), subtraction of resonant cross section (Tait)
- MCFM (Campbell, Tramontano) Veto if p_T of 2nd hardest b (or B) is too hard; suppress channels through scale choice
- What can one do in event generation?
- Can one actually define this process?

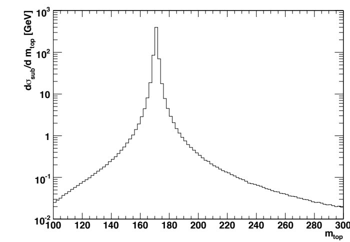
Can we define W+t as a process?

We also include p_T veto. Two approaches

- Remove resonant diagrams (DR) (- not gauge invariant)
- Constructed a gauge invariant, local counterterm. Diagram subtraction (DS)
- DS - DR is measure of interference

Momentum reshufling

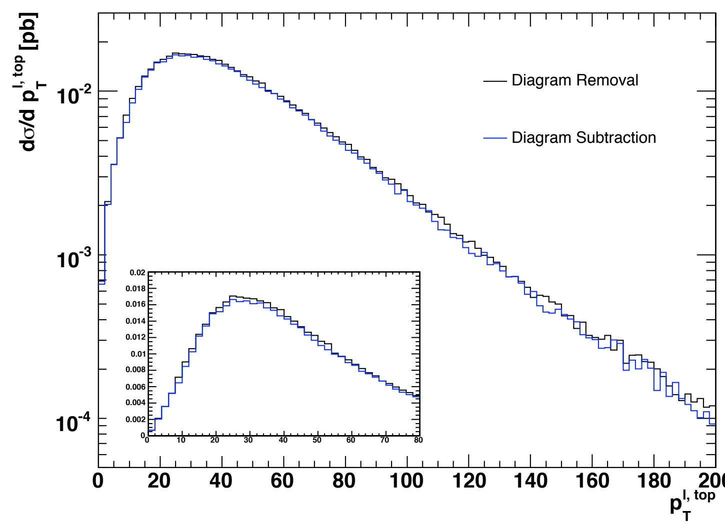
$$\tilde{\mathcal{D}}_{gg} = \frac{BW(M_{\bar{b}W})}{BW(M_t)} |A^{t\bar{t}}_{gg}|^2_{\text{reshuffled}}$$



$$d\sigma^{(2)} + \sum_{\alpha\beta} \int \frac{dx_1 dx_2}{2x_1x_2S} \mathcal{L}_{\alpha\beta} \left(\hat{\mathcal{S}}_{\alpha\beta} + \mathcal{I}_{\alpha\beta} + \mathcal{D}_{\alpha\beta} - \widetilde{\mathcal{D}}_{\alpha\beta} \right) d\phi_3$$

Compare

- Interference effects quite small
- Gauge variant result always very close to gauge invariant



Yes we can!

Conclusions

- Top physics: report on its every move
- Theory tools to do so already good, but keep remarkable pace of innovation
- Characteristics of production, decay very revealing
  - Top tells us its spin: angular distributions important
  - Precision of predictions important, and improving
- Top will remain “hot” for years to come..